

学校编码: 10384

密级_____

学号: 22420060153350

厦 门 大 学

博 士 学 位 论 文

浅海水声信道高效纠错编码技术研究

High-efficiency Error Correcting Code Techniques for
Shallow Water Acoustic Channels

刘胜兴

指导教师姓名: 许肖梅 教授

专 业 名 称: 海 洋 物 理

论文提交日期: 2009 年 12 月

论文答辩日期: 2009 年 12 月

2009 年 12 月

厦门大学学位论文原创性声明

本人呈交的学位论文是本人在导师指导下,独立完成的研究成果。本人在论文写作中参考其他个人或集体已经发表的研究成果,均在文中以适当方式明确标明,并符合法律规范和《厦门大学研究生学术活动规范(试行)》。

另外,该学位论文为()课题(组)的研究成果,获得()课题(组)经费或实验室的资助,在()实验室完成。(请在以上括号内填写课题或课题组负责人或实验室名称,未有此项声明内容的,可以不作特别声明。)

声明人(签名):

年 月 日

厦门大学学位论文著作权使用声明

本人同意厦门大学根据《中华人民共和国学位条例暂行实施办法》等规定保留和使用此学位论文，并向主管部门或其指定机构送交学位论文（包括纸质版和电子版），允许学位论文进入厦门大学图书馆及其数据库被查阅、借阅。本人同意厦门大学将学位论文加入全国博士、硕士学位论文共建单位数据库进行检索，将学位论文的标题和摘要汇编出版，采用影印、缩印或者其它方式合理复制学位论文。

本学位论文属于：

（ ） 1. 经厦门大学保密委员会审查核定的保密学位论文，
于 年 月 日解密，解密后适用上述授权。

（ ） 2. 不保密，适用上述授权。

（请在以上相应括号内打“√”或填上相应内容。保密学位论文应是已经厦门大学保密委员会审定过的学位论文，未经厦门大学保密委员会审定的学位论文均为公开学位论文。此声明栏不填写的，默认为公开学位论文，均适用上述授权。）

声明人（签名）：

年 月 日

摘 要

水声通信技术无论在军事还是民用领域均有重要应用价值。但由于水声信道,特别是浅海水声信道具有高噪、强多途及快速时变特性,从而使得实现能够可靠通信的系统极为困难。目前,无论采用相干,还是非相干调制方式的水声通信系统,通常都需要进行信道编码才能获得满足工程应用需求的低误比特率。

论文在对海洋中声传播特性及浅海水声信道特性进行理论研究的基础上,建立了浅海水声信道多途传输模型;在对各种信道纠错编码进行分析讨论的基础上,深入探讨了两种趋近香农限的高效信道纠错编码,即 Turbo 码和 LDPC 码在浅海水声信道中的性能。

论文的主要工作如下:

1. 系统推导了基于最大后验概率的软判决译码、软输入软输出 Viterbi 译码等 Turbo 译码算法;分析了设计参数对 Turbo 码性能的影响;提出了一种抗水声多途干扰、带循环判决反馈均衡的 Turbo 译码结构。仿真表明,当误比特率为 10^{-5} 时,该结构比判决反馈均衡器与 Turbo 译码器直接级连的结构性能优 2dB 左右。
2. 研究了校验矩阵 H 的结构、数据帧长、码率等参数对 LDPC 码性能的影响;研究了联合判决反馈均衡器时,规则 LDPC 码在浅海水声信道中的性能,将所得结果与 Turbo 码的结果进行比较可知, Turbo 码有编码简单、码率固定及在低 SNR 下性能优异等优点,而规则 LDPC 码有不出现错误平层、准确的纠错结果、译码算法简单、时延小及码率可以任意设置等优点。
3. 将水声跳频技术与信道编码技术相结合,提出了一种基于 MFSK 调制、FFT 解调和 Turbo 编译码(或 LDPC 编译码)的高效水声跳频通信系统,仿真表明该系统即使在较低 SNR 下也可获得极低的误比特率。
4. 在上述理论及仿真研究基础上,以 TMS320 C6713 DSP 为核心构建了水声跳频通信系统实验样机。该样机提出了一种联合窄带滤波和线性调频信号互相关检测的快速水声帧同步方法,软件方法实现了信号的调制/解调、Turbo 及 LDPC 码的实时编译码。

5. 大量水池及海上现场水声数据传输实验证实了所设计样机的有效性、可靠性及稳健性。在厦门港浅海实验中，当传输距离 3km 时，样机获得了速率 250bits/s、0 误比特率的通信性能；当传输距离为 5km 时，样机获得了速率 250bits/s、 10^{-5} 误比特率的通信性能。

本文创新之处在于：

1. 从理论上深入探讨了水声相干通信系统中 Turbo 码的性能，首次提出了一种抗多途干扰、带循环判决反馈均衡的 Turbo 译码结构；联合判决反馈均衡器，分析比较了 Turbo 码及 LDPC 码在浅海水声信道中的抗多途性能。
2. 首次以 TMS320 C6713 DSP 为核心构建了一套基于 MFSK 调制、FFT 解调和 Turbo 实时编译码（或 LDPC 实时编译码）的高效水声跳频通信系统实验样机；厦门港浅海水声数据传输实验证实了该样机的有效性、可靠性及稳健性。
3. 首次提出了一种联合窄带滤波和线性调频信号互相关检测的快速水声帧同步方法。

关键词：浅海水声信道；多途干扰；Turbo 码；LDPC 码；跳频通信

Abstract

Whether in military or civil use, underwater acoustic communication techniques have very important applications. It is very difficult to design an underwater acoustic communication system which can achieve reliable data transfer because the high noise, strong multipath and rapid time-varying exist in underwater acoustic channels, especially in shallow water acoustic channels. Now, whether in coherent or noncoherent underwater communication system, channel coding is often employed so as to achieve the bit error ratio which is low enough for satisfying the requirement of engineering application.

The propagation of sound in ocean and the features of shallow water acoustic channels are studied theoretically, based on which a multipath transfer model for the shallow water acoustic channels is presented. Furthermore, on the basis of analysing different kinds of error correcting code, the performance of two near Shannon limit high-efficiency error correcting code, namely Turbo and LDPC codes, is investigated in this dissertation.

The contents of the dissertation are as follows:

1. Some Turbo decoding algorithms, e.g., maximum a posteriori-based soft decision decoding and soft-input-soft-output Viterbi algorithm, are derived systemically. The influence of design parameters on the performance of Turbo code is analyzed. A new anti-multipath structure of Turbo decoder with iterative decision feedback equalizer (DFE) is built. Simulations show that the structure increase 2 dB in the performance compared with conventional Turbo decoder joint with DFE when bit error ratio is 10^{-5} .
2. The influences of the parameters such as the structure of the check-matrix H , length of the frame and code ratio on the performance of the LDPC code are analyzed. The performances of regular LDPC decoder joint with decision feedback equalizer in the underwater acoustic channels are investigated. The

result of LDPC decoder is compared with that of Turbo decoder, and it was found that the advantages of the Turbo decoder are that coding algorithm is simple, code ratio is fixed and the performance in low signal-to-noise ratio (SNR) is good, while the advantages of the LDPC decoder are that there is no error floor, correcting result is precise, decoding algorithm is simple, time-delay is short and code ratio is flexible.

3. A high-efficiency underwater acoustic frequency-hopping communication system is built by combining the underwater acoustic frequency-hopping and channel coding techniques. The MFSK modulation, FFT demodulation and Turbo coder/decoder (or LDPC coder/decoder) are employed in the above system. The simulation shows that the very low bit error ratio can be achieved even in low SNR environment.
4. Based on the above theories and simulations, an underwater acoustic communication experiment system is constructed by using TMS320 C6713 DSP as the core. The system introduces a new frame synchronization method by combining the techniques of narrowband filter and linear frequency modulation signal cross correlation detection. The modulation and demodulation of signals, and the real-time Turbo, LDPC coding and decoding are realized by the software method.
5. The validity, reliability and stabilization of the experiment system are proved by many underwater acoustic data transmission experiments which are carried out in a pool and in Xiamen harbor. The communication performances of the system achieved in the shallow water acoustic channels of Xiamen harbor are that the data rate is 250bits/s, the bit error ratio is 0 and the frame error ratio is 0 when communication distance is 3km, while the data rates is 250bits/s, the bits error ratio is 10^{-5} and the frame error is 10^{-3} when the communication distance is 5km.

The innovations of the dissertation are as follow:

1. The performance of Turbo code in high speed underwater acoustic coherent communication systems is studied theoretically, based on which a new anti-multipath structure of Turbo decoder with iterative decision feedback

equalizer is introduced first time. The performance of the Turbo code in shallow water acoustic channels is compared with that of LDPC code when the decision feedback equalizer is employed simultaneously.

2. A high-efficiency underwater acoustic frequency-hopping communication system is introduced. The MFSK modulation, FFT demodulation and Turbo coder/decoder (or LDPC coder/decoder) are employed in the system. Furthermore, an experiment system is constructed by using TMS320 C6713 DSP as the core. The experiments done in Xiamen harbor have proved the validity, reliability and stabilization of the system.
3. A new underwater acoustic frame synchronization method by combining the techniques of narrowband filter and linear frequency modulation signal cross correlation detection is introduced first time.

Key words: Shallow water acoustic channels; multipath interference; Turbo code; LDPC code; Frequency hopping communication

目 录

| | |
|-----------------------------|-----|
| 摘 要..... | I |
| Abstract..... | III |
| 第一章 绪 论 | 1 |
| 1.1 背景及研究意义 | 2 |
| 1.2 水声通信及其研究进展 | 3 |
| 1.2.1 水声通信系统概述..... | 3 |
| 1.2.2 水声通信研究进展..... | 5 |
| 1.3 水声信道高效纠错编码技术 | 7 |
| 1.3.1 信道纠错编码概述..... | 7 |
| 1.3.2 Turbo码..... | 8 |
| 1.3.3 LDPC码 | 9 |
| 1.4 研究内容 | 10 |
| 第二章 浅海水声信道的声传输特性 | 12 |
| 2.1 海洋的声学特性 | 12 |
| 2.1.1 海水中的声速..... | 12 |
| 2.1.2 海水中的声传播损失..... | 14 |
| 2.1.3 海洋内部的变异性对声学特性的影响..... | 16 |
| 2.1.4 海面声散射..... | 16 |
| 2.1.5 海底声散射和吸收..... | 18 |
| 2.2 水下噪声 | 18 |
| 2.2.1 海洋环境噪声..... | 18 |
| 2.2.2 舰船噪声..... | 20 |
| 2.3 浅海水声信道的主要特点 | 21 |
| 2.3.1 复杂性..... | 21 |
| 2.3.2 多变性..... | 22 |
| 2.3.3 强多途..... | 22 |

| | | |
|------------|-----------------------------------|-----------|
| 2.3.4 | 有限带宽和功率..... | 23 |
| 2.3.5 | 多普勒频移..... | 24 |
| 2.4 | 浅海水声信道与无线电信道的比较 | 25 |
| 2.5 | 小结 | 26 |
| 第三章 | Turbo码原理及设计参数对其性能的影响 | 27 |
| 3.1 | Turbo码的原理 | 27 |
| 3.1.1 | Turbo码的编码 | 27 |
| 3.1.2 | Turbo码的译码 | 28 |
| 3.2 | Turbo码的译码算法 | 31 |
| 3.2.1 | MAP算法 | 31 |
| 3.2.2 | Log-MAP算法 | 34 |
| 3.2.3 | Max-Log-MAP算法 | 36 |
| 3.2.4 | SOVA算法 | 36 |
| 3.2.5 | 译码算法复杂性分析..... | 40 |
| 3.3 | 设计参数对Turbo码性能的影响..... | 41 |
| 3.3.1 | 分量码生成多项式对Turbo码性能的影响 | 41 |
| 3.3.2 | 码率对Turbo码性能的影响 | 42 |
| 3.3.3 | 数据帧长对Turbo码性能的影响 | 42 |
| 3.3.4 | 迭代次数对Turbo码性能的影响 | 43 |
| 3.3.5 | 译码算法对Turbo码性能的影响 | 44 |
| 3.3.6 | 交织器对Turbo码性能的影响 | 45 |
| 3.3.7 | 信道交织对Turbo码性能的影响 | 46 |
| 3.4 | 小结 | 47 |
| 第四章 | 浅海水声信道中Turbo码性能研究 | 49 |
| 4.1 | 浅海水声信道模型 | 49 |
| 4.2 | 相干水声通信系统中Turbo码性能研究..... | 52 |
| 4.2.1 | 相干水声通信系统模型..... | 52 |
| 4.2.2 | 自适应判决反馈均衡器..... | 53 |
| 4.2.3 | Turbo译码与判决反馈均衡的级连结构 | 58 |
| 4.2.4 | 仿真结果及其分析..... | 61 |
| 4.3 | 水声跳频通信系统中Turbo码性能研究..... | 64 |

| | | |
|--|--------------------------------|-----------|
| 4.3.1 | 水声跳频通信系统模型..... | 64 |
| 4.3.2 | 水声跳频通信原理..... | 64 |
| 4.3.3 | 仿真结果及其分析..... | 68 |
| 4.4 | 小结 | 70 |
| 第五章 浅海水声信道中LDPC码性能研究 | | 71 |
| 5.1 | LDPC码的原理..... | 71 |
| 5.1.1 | 校验矩阵 H 的构造..... | 71 |
| 5.1.2 | LDPC码的编码 | 75 |
| 5.1.3 | LDPC码的译码 | 76 |
| 5.2 | LDPC码的性能分析..... | 80 |
| 5.2.1 | LDPC码的性能分析算法 | 80 |
| 5.2.2 | 非规则LDPC码的度分布的优化设计 | 84 |
| 5.3 | AWGN信道中LDPC码性能仿真 | 85 |
| 5.3.1 | 规则和非规则LDPC码的性能比较 | 85 |
| 5.3.2 | 不同码率时LDPC码的性能 | 86 |
| 5.3.3 | 不同数据帧长时LDPC码的性能 | 87 |
| 5.3.4 | LDPC码和Turbo码的性能比较..... | 88 |
| 5.4 | 浅海水声信道中LDPC码的性能仿真 | 88 |
| 5.4.1 | 传输函数对LDPC码性能的影响 | 88 |
| 5.4.2 | LDPC码和Turbo码的性能比较..... | 89 |
| 5.5 | 小结 | 90 |
| 第六章 水声跳频通信系统及Turbo编译码的DSP实现 | | 91 |
| 6.1 | TMS320C6713 DSP简介 | 91 |
| 6.1.1 | 硬件结构..... | 91 |
| 6.1.2 | 软件开发工具..... | 92 |
| 6.2 | 水声通信的帧同步技术 | 93 |
| 6.2.1 | 互相关检测法..... | 94 |
| 6.2.2 | 匹配滤波器或时频分析法..... | 94 |
| 6.2.3 | 联合窄带滤波和线性调频信号互相关检测方法..... | 95 |
| 6.3 | 水声跳频通信系统的DSP实现..... | 99 |
| 6.3.1 | 系统及硬件结构..... | 99 |

| | | |
|-----------------------------|---------------------------------|------------|
| 6.3.2 | 发射系统..... | 100 |
| 6.3.3 | 接收系统..... | 105 |
| 6.4 | 主机界面 | 110 |
| 6.5 | 小结 | 111 |
| 第七章 | 水声信道高效纠错编码实验及其结果分析 | 112 |
| 7.1 | 水池实验及其结果分析 | 112 |
| 7.1.1 | 海洋系水池实验及其结果分析..... | 112 |
| 7.1.2 | 部重水池实验及其结果分析..... | 117 |
| 7.2 | 海上实验及其结果分析 | 120 |
| 7.2.1 | 五缘湾海上实验及其结果分析..... | 120 |
| 7.2.2 | 厦门港海上实验及其结果分析..... | 123 |
| 7.3 | 小结 | 127 |
| 第八章 | 结论和展望 | 128 |
| 8.1 | 结论 | 128 |
| 8.2 | 研究展望 | 129 |
| 附 录 | | 131 |
| 参 考 文 献 | | 133 |
| 致 谢 | | 140 |
| 作者在攻博期间发表的学术论文 | | 141 |

Table of Contents

| | |
|--|------------|
| Abstract in Chinese..... | I |
| Abstract in English | III |
| Charpter 1 Intruduction | 1 |
| 1.1 background and Motivation..... | 2 |
| 1.2 Progress of Underwater Acoustic Commuincation..... | 3 |
| 1.2.1 Introduction to Underwater Acoustic Communication System | 3 |
| 1.2.2 Progress of Underwater Acoustic Communication..... | 5 |
| 1.3 High-efficiency Error Correcting Code Techniques for Underwater Acoustic Channel..... | 7 |
| 1.3.1 Introduction to Channel Error Correcting Code | 7 |
| 1.3.2 Turbo Code | 8 |
| 1.3.3 LDPC Code..... | 9 |
| 1.4 Research Questions..... | 10 |
| Charpter 2 Acoustic wave Propogation in Shallow Water Acoustic Channels | 12 |
| 2.1 Acoustic Properties of the Sea | 12 |
| 2.1.1 Sound Velocity in the Sea | 12 |
| 2.1.2 Transmission Loss in the Sea..... | 14 |
| 2.1.3 Influence of the Internal Variation in the Sea on the Acoustic Properties | 16 |
| 2.1.4 Acoustic Scattering from Ocean Surface..... | 16 |
| 2.1.5 Acoustic and Absorption from the Ocean Bottom..... | 18 |
| 2.2 Underwater Noise..... | 18 |
| 2.2.1 Enviromental Noise in the Sea..... | 18 |
| 2.2.2 Ship Noise..... | 20 |
| 2.3 Properties of Underwater Acoustic Channels | 21 |

| | | |
|---|--|-----------|
| 2.3.1 | Complexity..... | 21 |
| 2.3.2 | Variety..... | 22 |
| 2.3.3 | Strong Multipath..... | 22 |
| 2.3.4 | Limited Bandwidth and Power..... | 23 |
| 2.3.5 | Doppler Frequency Shift..... | 24 |
| 2.4 | Comparison Between Shallow Water Acoustic and Wireless Channels | 25 |
| 2.5 | Summary..... | 26 |
| Charpter 3 Theory of Turbo Code and Influence of Design | | |
| Parameters on its Performance..... | | 27 |
| 3.1 | Theory Turbo Code..... | 27 |
| 3.1.1 | Turbo Coding..... | 27 |
| 3.1.2 | Turbo Decoding..... | 28 |
| 3.2 | Turbo Decoding Algorithms..... | 31 |
| 3.2.1 | MAP Algorithm..... | 31 |
| 3.2.2 | Log-MAP Algorithm..... | 34 |
| 3.2.3 | Max-Log-MAP Algorithm..... | 36 |
| 3.2.4 | SOVA Algorithm..... | 36 |
| 3.2.5 | Complexity Comparison among Various Decoding Algorithms..... | 40 |
| 3.3 | Influence of Design Parameters on the Performance of Turbo Code | 41 |
| 3.3.1 | Influence of Polynomial..... | 41 |
| 3.3.2 | Influence of Code Ratio..... | 42 |
| 3.3.3 | Influence of Frame Length..... | 42 |
| 3.3.4 | Influence of Iterative Number..... | 43 |
| 3.3.5 | Influence of Decoding Algorithm..... | 44 |
| 3.3.6 | Influence of Interleaver..... | 45 |
| 3.3.7 | Influence of Channel Interleaving..... | 46 |
| 3.4 | Summary..... | 47 |
| Charpter 4 Performance Research of Turbo Code in Shallow Water | | |
| Acoustic Channels..... | | 49 |

| | | |
|---|---|-----------|
| 4.1 | Shallow Water Acoustic Channel Model..... | 49 |
| 4.2 | Performance Research of Turbo Code for Coherent Communication System in Shallow Water Acoustic Channels..... | 52 |
| 4.2.1 | Underwater Acoustic Coherent Communication System Model..... | 52 |
| 4.2.2 | Adaptive Decision Feedback Equalizer | 53 |
| 4.2.3 | Cascaded Structure of Turbo Decoder and Decision Feedback Equalize | 58 |
| 4.2.4 | Simulations and Analyses | 61 |
| 4.3 | Performance Research of Turbo Code for FH Communication System in Shallow Water Acoustic Channels | 64 |
| 4.3.1 | Underwater Acoustic FH Communication system Model | 64 |
| 4.3.2 | FH Communication Theory in Shallow Water Acoustic Channels..... | 64 |
| 4.3.3 | Simulations and Analyses | 68 |
| 4.4 | Summary..... | 70 |
| Chapter 5 Performance Research of LDPC Code in Shallow | | |
| Water Acoustic Channels | | 71 |
| 5.1 | Theory of LDPC Code..... | 71 |
| 5.1.1 | Construction of Check Matrix H..... | 71 |
| 5.1.2 | LDPC Coding..... | 75 |
| 5.1.3 | LDPC Decoding..... | 76 |
| 5.2 | Performance Analysis of LDPC Code..... | 80 |
| 5.2.1 | Performance Analysis Algorithms of LDPC Code..... | 80 |
| 5.2.2 | Optimization of Degree Distribution for irregular LDPC Code | 84 |
| 5.3 | Performance Simulation of LDPC Code in AWGN Channel..... | 85 |
| 5.3.1 | Performance Comparison Between regular and irregular LDPC Code.. | 85 |
| 5.3.2 | Performance of LDPC Code with different Code Ratio | 86 |
| 5.3.3 | Performance of LDPC Code with different Frame Length..... | 87 |
| 5.3.4 | Performance Comparison Between LDPC Code and Turbo Code | 88 |
| 5.4 | Performance Simulation of LDPC Code in Sallow Water Acoustic Channels..... | 88 |
| 5.4.1 | Influence of Transfer Function on the Perfromance of LDPC Code | 88 |
| 5.4.2 | Performance Comparison Between LDPC Code and Turbo Code | 89 |

| | | |
|---|--|-----|
| 5.5 | Summary..... | 90 |
| Chapter 6 DSP-based Realization of Turbo Coder/decoder and Underwater Acoustic FH Communication System.....91 | | |
| 6.1 | Introduction to TMS320C6713 DSP | 91 |
| 6.1.1 | Hardware..... | 91 |
| 6.1.2 | Software Developing Tools..... | 92 |
| 6.2 | Frame Synchronization for Underwater Acoustic Communication.... | 93 |
| 6.2.1 | Cross Correlation Detection..... | 94 |
| 6.2.2 | Matching Filter or Time-frequency Analysis..... | 94 |
| 6.2.3 | Combination of Narrowband Filter and linear frequency modulation signal Cross Correlation Detection..... | 95 |
| 6.3 | DSP-based Realization of Underwater Acoustic FH communication System | 99 |
| 6.3.1 | System Structure and Hardware..... | 99 |
| 6.3.2 | Sending System..... | 100 |
| 6.3.3 | Receiving System..... | 105 |
| 6.4 | PC Interface..... | 110 |
| 6.5 | Summary..... | 111 |
| Chapter 7 Experimental Results of the High-efficiency Error Correcting Code in Underwater Acoustic Channels112 | | |
| 7.1 | Experimental Result in Pools..... | 112 |
| 7.1.1 | Experimental Results in the Pool of the Department of Ocean | 112 |
| 7.1.2 | Experimental Results in the Pool of UAC | 117 |
| 7.2 | Experimental Results in the Sea | 120 |
| 7.2.1 | Experimental Results in the Wuyuan Gulf..... | 120 |
| 7.2.2 | Experimental Results in the Xiamen Harbor | 123 |
| 7.3 | Summary..... | 127 |
| Chapter 8 Conclusions and Forecasts128 | | |
| 8.1 | Conclusions..... | 128 |
| 8.2 | Forecasts | 129 |

Degree papers are in the "[Xiamen University Electronic Theses and Dissertations Database](#)". Full texts are available in the following ways:

1. If your library is a CALIS member libraries, please log on <http://etd.calis.edu.cn/> and submit requests online, or consult the interlibrary loan department in your library.
2. For users of non-CALIS member libraries, please mail to etd@xmu.edu.cn for delivery details.

厦门大学博硕士论文摘要库